The Navy's Application of Ocean Forecasting to Decision Support

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INTRODUCTION

Most of us rely each day on National Weather Service forecasts to plan our daily schedules. These forecasts are derived from a combination of numerical models and observations. Similarly, the US Navy requires ocean forecasts to support naval operations, including environmental information on ocean currents, waves, tides, sound speed, water temperature, salinity, and visibility. The Naval Oceanographic Office (NAVOCEANO) generates these ocean forecasts, and they are used by trained Navy oceanographers and forecasters to provide useful "ocean weather" information to the Navy's decision makers, allowing them to plan and operate more safely, efficiently, and effectively. Other papers in this special issue of *Oceanography* describe the research behind the development of these models. This article summarizes the main elements of NAVOCEANO's operational modeling systems in 2014.

SUMMARY OF OCEAN MODELS USED BY NAVOCEANO

Ocean modeling at NAVOCEANO takes a serial approach, starting each daily cycle with global prediction and scaling down to higher resolution regional and coastal domains (Figure 1). These ocean models, most of which were developed at the Naval Research Laboratory (NRL), output global, regional, and nearshore two- and three-dimensional ocean dynamic and thermodynamic properties and two-dimensional regional and coastal wave properties. NAVOCEANO ensures that these ocean models run on schedule, data are delivered in a timely fashion to Navy users, and interpretations of the information are provided, similar to the mission of the US National Oceanic and Atmospheric Administration's National Weather Service. Summaries of the ocean models used by NAVOCEANO follow.

Global Circulation Model

The HYbrid Coordinate Ocean Model (HYCOM), which was delivered from NRL as the Global Ocean Forecast System 3.0 (GOFS 3.0), is a four-dimensional ocean forecasting system that daily predicts the structure of ocean temperature, salinity, currents, and elevation through the next seven days, or 168 hours (Metzger et al., 2014, in this issue). Products include a two-dimensional global surface file and 18 three-dimensional regional data sets of all properties at three-hour intervals. Forty depth levels are output, expanding from a 1 m thickness at the surface to 1,000 m layers at deep ocean depths. The Fleet Numerical Meteorology and Oceanography Center (FLENUMMETOCCEN) half-degree NAVy Global Environmental Model (NAVGEM) provides the atmospheric forcing (Hogan et al., 2014, in this issue). HYCOM runs without tides, but barotropic tidal data from the Oregon State University Tidal Inversion Software (OTIS) are added after the model completes its run. A number of HYCOM data sets are delivered to the National Oceanic and Atmospheric Administration (NOAA) in real time. NOAA's National Centers for Environmental Prediction (NCEP)

provides public access to the model data via its Ocean Prediction Center (OPC) website for graphics or the National Operational Model Archive and Distribution System (NOMADS) for data files.

Regional Circulation Model

The Navy Coastal Ocean Model (NCOM) is a four-dimensional ocean forecasting system that daily predicts the structure of ocean temperature, salinity, currents, and elevation for the length of the atmospheric forecast, which is currently four days (96 hours). This model was developed at NRL as the Relocatable NCOM system (Rowley and Mask, 2014, in this issue). In specific areas of Navy interest, a Regional NCOM (RNCOM) is run at a horizontal resolution higher than that used by HYCOM. As each RNCOM runs, it obtains values along its open ocean boundaries from the HYCOM output fields in a procedure called nesting. Most RNCOM domains have a horizontal resolution of 1/30 degree. Even higher-resolution Coastal NCOM (CNCOM) domains are nested within some RNCOMs; these CNCOMs obtain values along their open ocean boundaries from the RNCOM within which they are nested. The resolutions of CNCOM domains are 300 m to 500 m. The typical size of an RNCOM domain is 20° of latitude by 20° of longitude, and the typical size of a CNCOM domain is 5° of latitude by 5° of longitude. The values at the HYCOM/RNCOM and RNCOM/CNCOM nest boundaries are transferred in only one direction, from the larger and coarser model to the smaller and higher-resolution model. Fields of RNCOM/CNCOM data are published daily at 3-hour/1-hour output intervals within the forecast period after initialization as Cooperative Ocean/Atmosphere Research Data Service (COARDS) NetCDF-4 files. Up to 40 depth levels are output, depending on the domain, using the same vertical layers as HYCOM. RNCOM output data

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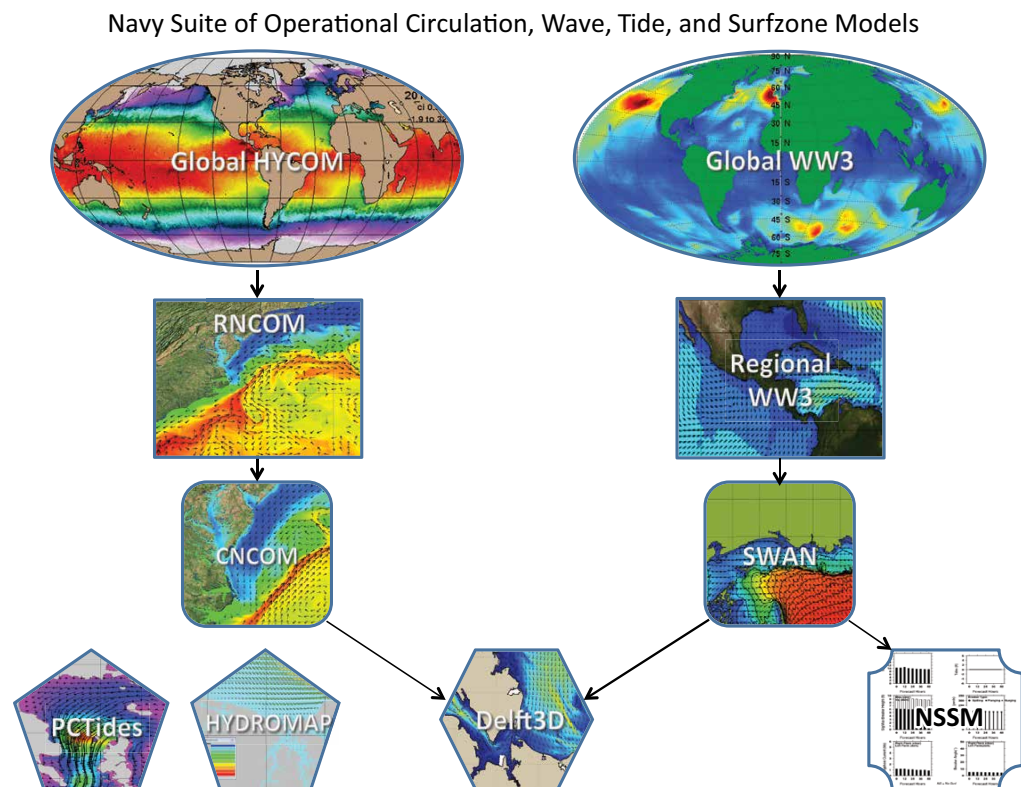## Navy Suite of Operational Circulation, Wave, Tide, and Surfzone Models

Figure 1. System flow diagram of ocean and wave models from global to coastal scales run daily at the Naval Oceanographic Office (NAVOCEANO).

» HYCOM = HYbrid Coordinate Ocean Model
» WW3 = WAVEWATCH III
» RNCOM = Regional Navy Coastal Ocean Model
» CNCOM = Coastal Navy Coastal Ocean Model
» PCTides = Two-dimensional baro-tropic tidal model
» HYDROMAP = A commercial three-dimensional, PC-based, globally relocatable model
» Delft3D = A commercial coastal and estuarine circulation model
» SWAN = Simulating WAves Nearshore
» NSSM = Navy Standard Surf Model

See text for descriptions of these models.

sets, which cover United States coastal areas, are delivered like HYCOM output to NOAA's websites in real time.

Ice Forecasts

NAVOCEANO runs the NRL-developed Arctic Cap Nowcast/Forecast System (ACNFS), which encompasses all ice covered seas from 40°N–90°N latitude. ACNFS (Metzger et al., 2014, in this issue) uses the Los Alamos National Laboratory Community Ice CodE (CICE) for its ice model and uses an Arctic regional HYCOM for its ocean model. CICE and HYCOM are coupled by exchanging properties at a high temporal resolution during a synchronized run through the Earth System Modeling Framework (ESMF; Collins et al., 2005). A number of output fields, including ice coverage, thickness, drift, temperature, salinity, and currents, are delivered to the National Ice Center (NIC) to provide guidance to forecasters. NCEP also receives this model guidance for service to National Weather Service users and the public. In the near future, ACNFS will be discontinued as an independent model, and CICE will be coupled within the global HYCOM system for both the Arctic and Antarctic regions.

Regional Coupled Modeling

In 2012, initial implementation of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) was completed at NAVOCEANO. COAMPS couples the separate ocean and atmosphere models by exchanging variables between them as they run to provide a single virtual model containing both environments (Figure 2). NRL is finalizing inclusion of the wave model component in COAMPS (Allard et al., 2014, in this issue) and will then add an ice model component to the

system. The core models are COAMPS for the atmosphere, NCOM for the ocean, WAVEWATCH III (WW3) or Simulating WAves Nearshore (SWAN) for waves, and CICE for ice forecasting. Note that even though the name states it is coupled, COAMPS was first developed as a stand-alone, uncoupled atmospheric model, and its recent evolution is producing a fully coupled solution. COAMPS currently uses 3D Variational (3DVAR) data assimilation and will soon be upgraded to use 4D Variational (4DVAR) data assimilation. An advantage of 4DVAR is that observations will have larger impacts on the predictions as the system dynamics propagate the information through space and time.

The exchanges of relevant field variables between COAMPS system components are conducted via ESMF software, and the added feedback physics contribute to an improved forecast for each environment. While the components are all contained in COAMPS, any single component will be able to run with externally provided inputs from the others, if desired. One by one, NAVOCEANO plans to replace regional and coastal stand-alone NCOM domains with COAMPS. In the next few years, what is learned via COAMPS implementation will be applied to a global coupled modeling system, the Earth System Prediction Capability (ESPC; Burnett et al., 2014, in this issue).
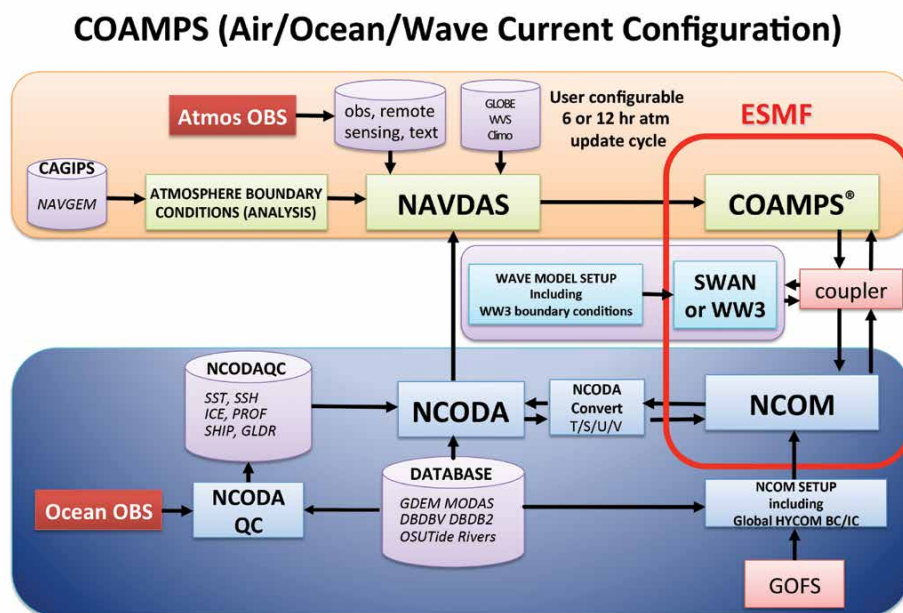

Figure 2. Flow diagram of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) in its atmosphere-ocean-waves configuration. The atmosphere core model highlighted in orange, the ocean core model in blue, and the wave core model in purple.

» CAGIPS = Come And Get It Product Service
» ESMF = Earth System Modeling Framework
» GOFS = Global Ocean Forecast System.
» NAVGEM = NAVy Global Environmental Model
» NCODA = Navy Coupled Atmosphere/Ocean Data Assimilation
» NCOM =Navy Coastal Ocean Model
» NAVDAS = NRL Atmospheric Variational Data Assimilation System, the atmospheric equivalent to NCODA

The following are topography inputs:
» GLOBE = Global Land One-km Base Elevation
» WVS = World Vector Shoreline
» DBDB2 = Digital Bathymetry Data Base 2 minute resolution
» DBDBV = Digital Bathymetry Data Base variable resolution

Very High-Resolution Coastal Circulation Models

Nearshore elevation and current predictions are available at NAVOCEANO from the HYDROMAP, PCTides, and Delft3D models. HYDROMAP is a commercial three-dimensional, PC-based, globally relocatable model developed by Applied Science Associates (ASA). Horizontal resolution typically ranges from 50 m to 500 m, and vertical resolution is unique for each area. Barotropic currents and surface elevation fields are predicted over 48 hours. This model is used for rapid response to requests, as it is quick to set up and uses a simplified rectangular grid with the capability to create increasingly higher resolution nests. It outputs data that users can read using ASA's Meteorology and Oceanography (METOC) Model Viewer software. Offshore boundary conditions for HYDROMAP are tidal elevation and currents derived from the Oregon State University TOPEX 5.1 analyses and atmospheric forcing provided from COAMPS.

PCTides is a two-dimensional barotropic tidal model developed by NRL. The Finite Element Solution (FES-2004) global tide model provides initial and boundary conditions. PCTides may be forced by winds and surface pressure and can assimilate tide station data from the International Hydrographic Office tidal database. PCTides is quick to set up and can be nested down to as fine as 100 m resolution. It has been configured to run on PCs or a Department of Defense (DoD) Supercomputing Resource Center (DSRC) computational server. This model also has a rectangular grid and can be implemented anywhere in the world to support emergency operations. PCTides provides realistic two-dimensional predictions of tidal currents and elevation to 96 hours.

Delft3D is a commercial coastal and estuarine circulation model that is now freely available from Deltares and implemented operationally at NAVOCEANO with help from NRL. It can be set up in either two or three dimensions and can be coupled with a high-resolution wave model, if required. Delft3D has an advantage over the previously discussed models in that it can use irregular grids to represent complex, realistic nearshore bottom topography and coastlines. However, this model is more complicated and time consuming to implement and run, so it is not a "quick response" capability like those described above. COAMPS provides atmospheric forcing, and ocean boundary conditions and sea surface elevation are obtained from the lower-resolution NCOM domains or by tidal stations. Delft3D model horizontal resolution typically ranges from 10 m to 200 m, and its output extends up to 72 hours. Figure 3 shows example products from Delft3D, including coastal currents for the Chesapeake Bay domain, with an insert showing tidal elevations and vertical current structure over time at a point near the mouth of the bay.

Global, Regional, and Coastal Wave Model

FLENUMMETOCCEN and NAVOCEANO share wave modeling tasks for the Navy, with FLENUMMETOCCEN's WW3 covering large basin areas and NAVOCEANO's SWAN providing coastal wave and surf predictions (Rogers et al., 2014, in this issue). NAVOCEANO also runs a global multigrid WW3 to provide spectral boundary conditions for regional and coastal SWAN domains. WW3 is a third-generation spectral wave model developed at NOAA's NCEP, and the operational version was transitioned by NRL to NAVOCEANO.

NAVOCEANO runs a large number of SWAN domains to forecast various wave parameters ranging from significant wave and swell height to wave steepness. Resolutions range from ~ 1/12 degree or six and a half kilometers for regional domains to 10 m for very nearshore coastal domains, depending on requirements and the availability of high-resolution gridded bottom topography. SWAN is a third-generation, phase-averaged wave model developed at the Delft University of Technology. Although it is part of the Delft3D modeling package, it is currently implemented as a stand-alone model at NAVOCEANO. SWAN is also linked with the Navy Standard Surf Model to generate surf forecasts at individual beach locations.

NAVOCEANO OCEAN MODEL SETUP, ATMOSPHERIC FORCING, AND DATA ASSIMILATION

To model the ocean properly, certain environmental data are needed, including an accurate representation of the ocean bottom and the coastline, real-time energy exchanges at the surface due to atmospheric forcing, and observations for assimilation. FLENUMMETOCCEN supplies all atmospheric information, as mentioned earlier, and NAVOCEANO supplies all oceanic information.

Bottom Topography for Ocean Models

The accuracy of an ocean model depends on a proper definition of the "basin" in which the water resides. The shape, composition, and frictional characteristics

of the bottom to some degree affect mass conservation, momentum and heat transports, tidal elevation, and current structure. This dependency is especially true in the coastal regions where the prediction of currents, wave steepening, surf characteristics, or storm surge and inundation require accurate and consistent information about the bottom from deepwater regions, across the shelf, over the beach, and into the foreshore.

For the past two centuries, NAVOCEANO and its predecessors have been leaders in the collection, analysis, and delivery of bottom topography and geology data for many Navy and national applications, including ocean modeling efforts. A fleet of survey ships, lidar-equipped aircraft, high-resolution multispectral satellites, and specialized on-scene collection teams gather highly accurate data. Data extracted from NAVOCEANO's massive global bottom topography holdings are provided to the ocean modelers, ensuring that they are working with the best available bottom structure.

Atmospheric Forcing

A primary driving factor for all of NAVOCEANO models is the effect that the atmosphere has on the ocean surface. As noted earlier, NAVOCEANO relies on output data from NAVGEM for global HYCOM and from COAMPS to force regional NCOM model and coastal model domains.
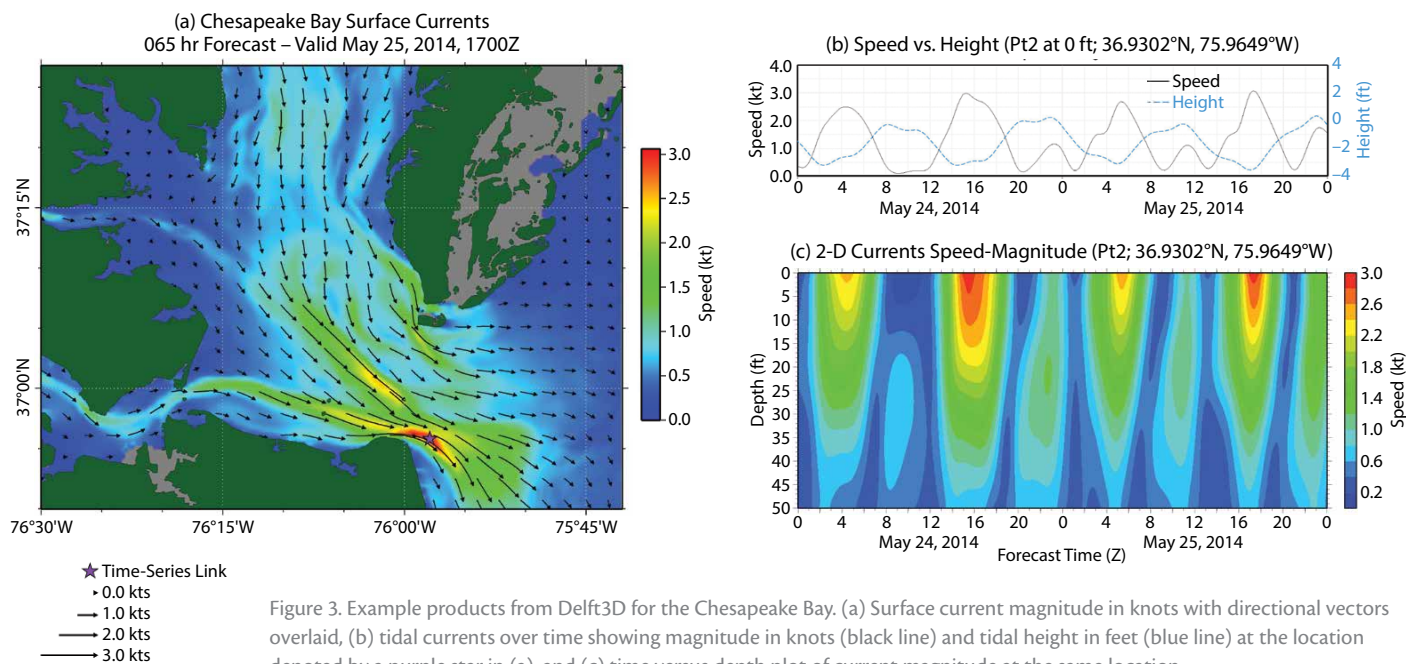
Daily, NAVOCEANO receives over 47,000 files of atmospheric fields from FLENUMMETOCCEN through the Come And Get It Product Service (CAGIPS) that includes surface (or 2 m) air temperature, ground or sea temperature, pressure, ice coverage, dew point depression, specific humidity, vapor pressure, infrared (longwave) flux, solar (shortwave) flux, sensible heat flux, latent heat flux, total precipitation, eastward and northward surface wind stress, and eastward and northward wind speeds at 10 m. To ensure these fields properly force the ocean models, NRL has developed a set of monthly calibration factors to optimize these exchanges. The current 2014 version of NAVGEM is provided

at a 1/2 degree (55 km) resolution; however, an aggressive program to increase the resolution to about 15 km (8 nm) is underway. Most COAMPS fields for the regional NCOMs are delivered at 15 km–18 km (8 nm–10 nm) resolution.

Ocean Observations Acquisition, Processing, Dissemination, Quality Control, and Analysis

A major function of NAVOCEANO is the timely reception, processing, archiving, and dissemination of a wide range of ocean field estimates. Real-time observations are important to operational oceanography because they provide the capability to perform the following functions: (1) assimilation that corrects analyses' fields prior to each model run; (2) assessment that ensures the models are on track, determines their skill level, and evaluates new models or upgrades; and (3) production where observation-based historical or climatological views of the ocean are created.

Observations are broadly categorized as either remotely sensed (i.e., retrieved,

Figure 3. Example products from Delft3D for the Chesapeake Bay. (a) Surface current magnitude in knots with directional vectors overlaid, (b) tidal currents over time showing magnitude in knots (black line) and tidal height in feet (blue line) at the location denoted by a purple star in (a), and (c) time versus depth plot of current magnitude at the same location.

for example, by satellites or coastal radars) or in situ (i.e., directly measured by ocean platform instruments). Observational data need to be timely and accurate for improving NAVOCEANO's ocean modeling to meet Fleet users' need for reliable, real-time information. Erroneous observations and data that are more than a couple of days old do nothing to improve model initialization and can actually induce undesired results.

The high-quality remotely sensed data received at NAVOCEANO are delivered from a wide range of satellite platforms that collectively retrieve sea surface temperature (SST), altimetry or sea surface height (SSH), ice characteristics, and wave data.

NAVOCEANO is a national acquisition, processing, fusion, and distribution center for SSH and SST data. Altimetry is important for defining the mesoscale ocean structure (e.g., ocean eddies, fronts, and meandering jets) in global and regional models. In addition to being assimilated into NAVOCEANO models, these data are processed through NAVOCEANO's Altimetry Data Fusion Center and made available to other agencies for their ocean analysis and modeling efforts. Because of dwindling altimetry platforms, the Navy meteorology and oceanography community has been emphasizing the need for a robust international altimetry program.

NAVOCEANO operationally produces SST retrievals from several polar orbiting and geostationary satellites, and the composited results are disseminated as a Multi-Channel Sea Surface Temperature (MCSST) product. SST retrievals are also obtained from international satellite partners through participation in the Group for High-Resolution Sea Surface Temperature project. Ice characteristics are retrieved from passive microwave and infrared satellite sensors, passed to the NIC for polar ice analysis, and assimilated into the ACNFS.

NAVOCEANO's Real Time Data Handling System (RTDHS) is a collection and collation site for in situ surface and subsurface observations from shipboard conductivity-temperature-depth (CTD) systems, eXpendable BathyThermographs (XBTs), buoys, profiling floats, drifters, gliders, marine animals, and other platforms. In situ data are sparse compared to those collected in the atmosphere, so every oceanographic observation is considered important. In addition to the real-time data stream of the World Meteorological Organization's Global Telecommunication System, RTDHS receives military observation messages and data from a number of cooperative academic, commercial, and international partners. The RTDHS automatically quality checks, decodes, and reformats all observations received from these multiple sources and delivers them to the ocean model assimilation system in a timely (on the order of minutes), consistent, and readable format.

NAVOCEANO deploys and controls its own suite of observation platforms that include ships, profiling floats, drifters, and gliders. NAVOCEANO strives to use these assets to improve its ocean models by placing them where they can have the most impact. In the case of glider deployments, NRL designed a Glider Observation Strategy that uses the modeled ocean environment (including three-dimensional currents) to direct gliders. Every 12 hours, this direction provides glider waypoints or target positions that should be attainable according to modeled current speeds and environmental data that come from the glider itself.

Once the various types of observations have been received and processed into standard data formats, they proceed through a two-step assimilation process using the Navy Coupled Atmosphere/Ocean Data Assimilation (NCODA) system to make the information usable by the models. The first step, NCODA OceanQC, is a stand–alone mode that supports automated ocean data quality control. In this step, near-real-time ocean observations from both remotely sensed and in situ sources are processed by NCODA OceanQC and assigned probability of error (POE) values based on a priori knowledge of their sources, their ages, comparisons with nearby observations, and differences from background fields. These background fields are drawn from a previous NCODA analysis or a model run (the second step, discussed below). The POE values are translated into weighting factors or used to eliminate or reduce the effects of errant data in ocean model runs.

The second step is the main NCODA system. This system can run in a stand-alone version that supplies the background fields for NCODA OceanQC, or it can run as a pre-processing step in the ocean models (Metzger et al., 2014, and Rowley and Mask, 2014, both in this issue). This NCODA system compares observed ocean data to the previous day's model forecast (background field) and provides innovations or corrections to that background field for application prior to the start of the next model cycle. The Navy's Modular Ocean Data Assimilation system (MODAS; Fox et al., 2002) is a component of NCODA that is used to create subsurface data in the form of "synthetic" ocean temperature and salinity profiles. These synthetic profiles are calculated from the observed SSH and SST data using statistical

relationships derived from historical ocean profiles that are part of the NAVOCEANO databases.

DoD'S SUPERCOMPUTING RESOURCE CENTER

Operational ocean models require a major commitment in computational power. NAVOCEANO is uniquely positioned to take advantage of a world-class computing capability within the DSRC. Through a cooperative agreement with the DoD High Performance Computer Modernization Program (HPCMP), 15% of the Navy DSRC computational and storage assets at Stennis Space Center are designated for Navy modeling operations. While other DSRCs deliver high performance computational capabilities to both the DoD science and technology and test and evaluation communities, the state-of-the-art supercomputers at Stennis are managed with a concern for full-time operational support.

The Navy DSRC systems are configured so that research and development (R&D) and production oceanography users are placed in separate partitions, currently with about 140 teraflops dedicated to NAVOCEANO and FLENUMMETOCCEN. The DSRC systems are typically acquired on a two-year schedule with each new system expected to remain in operation for four years. The 2012 installation of new hardware represented more than a threefold increase in the center's computational capacity.

THE NAVOCEANO MODEL OPERATIONS TEAM

The oceanographic operational production center at NAVOCEANO routinely prepares and delivers to Fleet users a large set of products that includes ocean model output files and graphics from circulation, and daily wave models over their full prediction cycle. This capability is the responsibility of the Model Operations Team, which maintains schedules, monitors daily progress, finds and repairs issues, responds to requests for services, and manages changes in systems, software, and requirements. This effort requires a dedicated group of people with a wide range of skills

that include conducting operations on various computational platforms (from supercomputers to Windows and LINUX desktops), creating and managing ocean models, scripting model processing, and troubleshooting problems. To ensure the production system is maintained uniformly, an extensive and dynamic collection of standard operating procedures is maintained.

In addition, the Model Operations Team uses a database system called Rapid Ocean Atmosphere Model Environment, Relocatable (ROAMER) to record and keep track of events, maintain schedules, allow quick progress evaluations via Web pages, provide alerts when issues occur, and suggest solutions to common problems. Other functions include acquisition and preparation of

atmospheric forcing, process monitoring, control of the submission and setup for wave models, post-processing of data and graphic outputs for all ocean models, and delivery of forecast products internally and externally. ROAMER is the backbone that makes everything work together as an operational system.

The Model Operations Team maintains a close relationship with NRL

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developers to resolve issues, establish requirements, suggest improvements, and help transition new capabilities or upgrades from the research machines into the operational run stream. This team also works with Navy customers to quickly supply data or graphics to support their operations.

THE OCEAN FORECASTERS

To help the Navy customer understand, synthesize, and better utilize ocean model data, a cadre of civilian ocean forecasters has been drawn together at NAVOCEANO. With varied academic backgrounds, these forecasters provide a broad skill set that forms the backbone for ocean forecasting at NAVOCEANO as they study the full water column, concentrating on how Navy ships and

sensors interact with this environment. They develop skills in physical oceanography, ocean modeling, meteorology, ocean acoustics, ocean sensors, data assimilation, data analysis, and computer science. Each ocean forecaster specializes in a geographical area and/or a forecaster function such as a specific model or tool. While a request for support may be funneled to the person

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with the highest related expertise, open discussions among team members help to maintain a broad base of knowledge among them so that most requests can be filled by any member of the team, ensuring that all requests are completed quickly and fully.

OCEAN CLIMATOLOGY

Ocean forecasters are often asked what will the ocean environment be beyond the current modeling predictions. Presently, ocean model predictions go out to seven days, but the Fleet needs to know what the ocean environment will be weeks, months, and years in advance when planning operations. To provide this information, NAVOCEANO creates climatology products from its ocean observation and model archives, as well as from the scientific literature, in order to estimate and describe typical regional

ocean parameters and their variability in the context of future operational situations. A new source of historical data for building Navy ocean climatologies is NRL's HYCOM re-analyses, a historical, global model run going back to 1992, using the best atmospheric forcing and observation data sources available.

Ocean climatology products may include statistics of current flows derived from multiple years of model current fields combined with historical observations. Products available for Fleet use include historical drift probability maps and statistics overlaid on speed and direction at multiple depths. These drift plots are used to determine where an object may drift to at a given time, or inversely, where a found object may have originated. Another example of a Navy ocean climatology product is the Generalized Digital Environmental Model (GDEM) database developed by NRL and NAVOCEANO. GDEM is a global, monthly, full-depth, 78-vertical level, gridded climatology of the means and standard deviations of temperature and salinity. These data provide ranges of values to estimate variability, in order to quality control observations for model assimilation and to evaluate model forecasts.

HOW OCEAN MODEL PRODUCTS SUPPORT NAVY APPLICATIONS

A large suite of up-to-date ocean model graphics and data is posted daily for Fleet users via a DoD-only Web portal. This site includes JPEG images of ocean temperature, salinity, surface elevation, and currents at multiple depths and time steps. The site also presents forecasts of wave properties such as significant wave height, mean wave direction, and mean wave period graphics. With the click of a button, a Navy customer can investigate modeled forecast conditions and add relevant images to an operational brief. This site also makes compressed data files available for customers who have the appropriate tactical software.

NAVOCEANO's Customer Service Office (CSO) centrally manages special customer requests. When CSO is contacted for products or information, a request for service is generated and assigned to the appropriate department for completion. CSO and NAVOCEANO analysts interact directly with the customer to ensure that the information provided will be useful, complete, and delivered on time. For ocean model products, the information supplied may take many forms. It may be sent out directly or posted for real-time access on the Web portal. Government partners may be provided access to model data via the archives at the DSRC, or data could be extracted and mailed on DVDs.

An important example of an ocean forecaster product is the Tactical Oceanographic Feature Assessment (TOFA; Figure 4). This product is a Microsoft PowerPoint- or Google Earth-compatible file with plots of model variables such as temperature or currents with overlays of features such as major currents, temperature fronts, and

eddies. The file is followed by in-depth discussion of how the information presented could affect operations in the dynamically evolving ocean at scales from hours to days. Estimates of uncertainty and, in some cases, recommendations for best use of the environment or alternate approaches may be added. The TOFA may also include answers to specific questions based on the synthesis of historical or climatological data at NAVOCEANO. In many cases, cooperative exchange of ideas with the Navy personnel afloat is necessary to ensure forecast products provide the best possible operational support.

The Navy is often first on scene to assist with disasters such as typhoons, earthquakes, lost people and gear, or oil spills. NAVOCEANO has specialized capabilities to respond quickly to these events, either alone or in cooperation with national partners such as NOAA and the US Coast Guard as well as with international partners. These capabilities include probabilistic and deterministic forecasts for drifting objects (Figure 5) and oil dispersion, as well as forecasts of high seas and storm surge when tropical weather systems make landfall.

OCEAN FORECAST SKILL

A continuing challenge for ocean modeling is to demonstrate that the forecast is reliable or that it has skill. For NAVOCEANO circulation models (HYCOM/NCOM), various ocean field variables, such as currents, temperature, and salinity and their vertical gradients at selected depths, are compared to available observations and historical studies to determine the skill of their output. Ocean model output is evaluated by comparison to appropriate measurements acquired from the varied sources discussed in the "Ocean Observations Acquisition" section above. Specific mesoscale ocean features, such as eddies, are also identified in these remote measurements and compared to the same features predicted by the models. In some modeled areas, where ocean measurements are sparse or unavailable, comparisons are made to trends found in the literature, to climatology, or to output from other models set up in the same or a similar region. Many of these comparisons are qualitative in nature, but NAVOCEANO also has tools to quantitatively compare observations to models. Recent comparisons indicate a relatively slow decay in ocean forecast skill for both HYCOM and NCOM as the forecast period increases, reassuring users that these ocean prediction fields can be used with confidence throughout the four- to seven-day forecast period.

FUTURE OCEAN MODELING PLANS

Over the next few years, NAVOCEANO, in cooperation with NRL and FLENUMMETOCCEN, is planning a number of model improvements, upgrades, and new capabilities that
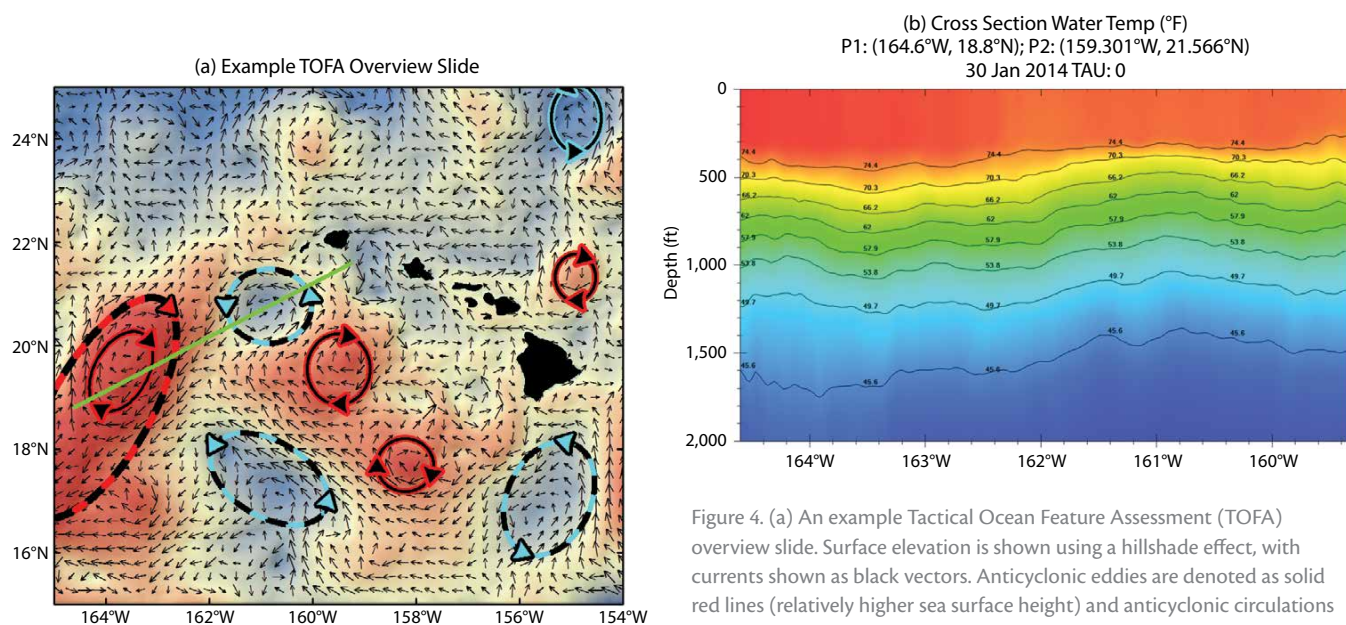

Figure 4. (a) An example Tactical Ocean Feature Assessment (TOFA) overview slide. Surface elevation is shown using a hillshade effect, with currents shown as black vectors. Anticyclonic eddies are denoted as solid red lines (relatively higher sea surface height) and anticyclonic circulations of importance are denoted by dashed red lines. Cyclonic eddies are solid turquoise lines and cyclonic circulations of importance are denoted by dashed turquoise lines. The green line shows the extent of the vertical cross-section graphic (b) that displays the vertical temperature structure across several features.

promise to advance NAVOCEANO's operational service to the Fleet. These improvements include (1) the addition of baroclinic tidal forcing within HYCOM, (2) a better synthetic profile capability where no subsurface observations are available, (3) higher horizontal resolution of all ocean models, and (4) data assimilation using a 4DVAR approach, to name a few on the near horizon.

In the present approach, HYCOM does not produce a full three-dimensional, tide-induced ocean structure. Future HYCOM versions will contain a full tidal solution. Better synthetic profiles are needed inside NCODA. A new method, the Improved Synthetic Ocean Profile project (Helber et al., 2013), based on vertical gradients and three-dimensional correlation functions, has been developed to improve this capability. The 4DVAR assimilation technique has been applied to atmospheric assimilation for a number of years, but only recently have NRL scientists been able to demonstrate that it can improve ocean predictions while using a reasonable number of computational processors as well as a reasonable amount of time. These projects are expected to improve the models' ability to predict changes in the mixed layer, a major weakness at present.

Further improvements to model predictions are anticipated as NAVOCEANO obtains greater access to new data sets and forcing information. The NAVOCEANO glider fleet continues to expand toward the goal of 150+ gliders. These gliders can be autonomously deployed for up to six months or even longer for oceanographic data collection based on the sensor strategies noted earlier. Optical and current sensors will be added along with CTD sensors. A project to use satellite-observed atmospheric fluxes will be implemented to allow real-time correction of FLENUMMETOCCEN global model forcing fields. A number of projects are underway to supply additional higher resolution ice observational data for assimilation.

As computational capacity in the DSRC increases, NAVOCEANO will work to increase the resolution of all models. The plan is to implement a 1/25 degree global HYCOM in 2016, and similar upgrades to WW3 are expected. With increased DSRC capability and improvements in model ensemble efficiency, NAVOCEANO will soon be able to add ensemble-based uncertainty estimates to its product suite.

Future versions of COAMPS represent the first successful step toward a fully coupled modeling environment, where exchanges between the ocean, atmosphere, ice, land, hydrosphere, biosphere, and space occur in real time. The ESPC that was mentioned in the "Summary of Ocean Models at NAVOCEANO" section is expected to reach an initial Navy operational capability around 2018. With enough computer power and storage, daily to seasonal or longer predictions will become available routinely.

As the product suite expands and resolution increases, the volumes of ocean model data that NAVOCEANO produces are increasing by leaps and bounds. Methods to better manage, analyze, transport, archive, purge, mine, and extract these fields are needed. This issue is not confined to the daily production cycle; in the near-term, the completion of a 20+ year HYCOM climatology at unprecedented temporal and spatial resolutions is anticipated. The intelligent extraction of climate or historical data for Navy strategic planning presents a challenge. These sorts of massive data problems are not confined to NAVOCEANO, and this is an active area where the R&D community can help.
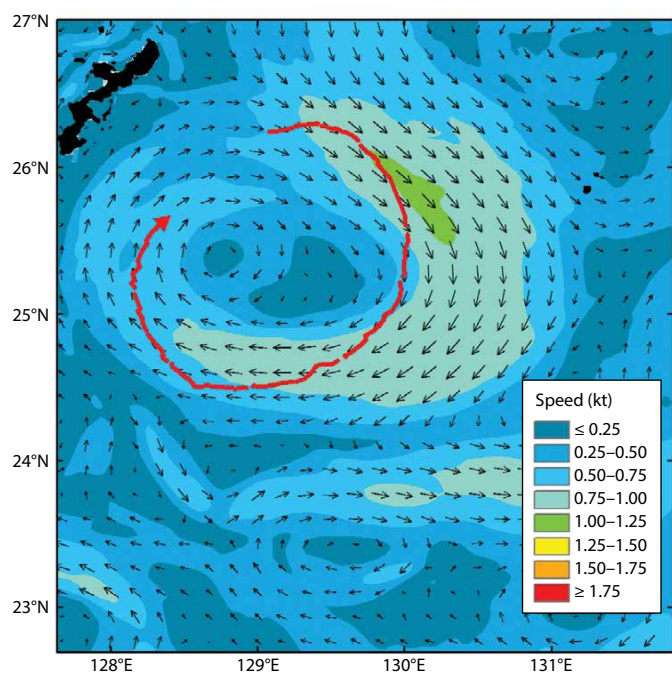
ACKNOWLEDGEMENTS

Figure 5. A comparison of the Western Pacific RNCOM average currents (March 29–April 5, 2014) in knots to a surface drifter track for March 25 to April 8, 2014. These qualitative results show that the model is accurately predicting this eddy.

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